THE USE OF SURFACE WAVE TECHNIQUES FOR VERIFICATION OF DYNAMIC RIGIDITY MEASUREMENTS IN A KAOLINITE-WATER ARTIFICIAL SEDIMENT

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THESIS

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ABSTRACT

A three-dimensional model for the study of surface wave speed measurements in simulated ocean bottom sediments has been constructed using a high-porosity kaolinite-water mixture in a rectangular tank in the laboratory. The propagation of surface waves, assumed to be Rayleigh waves, was studied over the 75 Hz to 300 Hz frequency range using a gated sine wave source and several geophone receivers. Shear wave speeds in the sediment are determined to be 23 m/sec. These measurements are qualitatively compared with measurements made by previous investigators in similar sediments using a torsionally oscillating rod viscoelastometer whose resonant characteristics are sensitive to loading by the sediment in which it is imbedded. Good correlation of results is found with the shear wave speeds calculated from the viscoelastometer data which are in the range of 20 to 30 m/sec.

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I. INTRODUCTION

In recent years research into the acoustic properties of ocean bottom sediments has been greatly accelerated. This increased interest is due in part to the necessity for improving the capability for predicting the acoustic reflection characteristics of the ocean floor which have important effects on sound propagation in shallow water, on the bottom bounce mode of sonar operation and on long-range acoustic propagation.

Early efforts in this area dealt with a two-fluid model of the ocean bottom. This model is often called the Rayleigh model and has been generally successful due to the low rigidity (i.e., nearly fluid character) of most surficial ocean bottom sediments. This model is not always satisfactory, however, since it predicts lower than observed bottom losses, particularly at low grazing angles. Bucker, Whitney, and Keir (3), have attempted to resolve this anomaly by assuming that the sediment is capable of supporting a shear wave. Using a more realistic viscoelastic model, it is possible to account for additional absorption due to some of the energy of the compressional wave being converted into shear waves at the sediment interface. The problem then becomes that of calculating the reflection coefficients for the viscoelastic layer using complex Lamé constants. This model has been applied, with reasonable

success (3), to help explain results from experiments conducted off the coast of Southern California.

An important difficulty in applying the viscoelastic model is that of providing good values for the complex elastic moduli which must be determined from measurements of the sound absorption, shear wave speed and compressional wave speed in the sediment under consideration. The rigidity values used by Bucker, Whitney and Keir, were obtained by Hamilton, et al.(12), using Stoneley wave techniques. Hutchins (14) demonstrated the feasibility of determining the shear wave speed in a laboratory prepared kaolinite-water artificial sediment using a torsional wave viscoelastometer. This instrument was an adaptation of an instrument which had formerly been used in the measurement of viscoelastic properties of polymer solutions. This method analyzes the loading effects on a torsionally vibrating rod caused by the rigidity of the sediment. Hutchins developed the viscoelastometer in the frequency range of 38.3 to 38.9 kHz.

Cohen (5) was able to improve the design of the viscoelastometer and extended its range of operation to 5.8 to 38 kHz. His experiments were performed in kaolinite-water and bentonite-water artificial sediments.

Utilizing the fact that rigidity measurements were possible with the viscoelastometer, Bieda (2) developed a probe useful for in situ measurements and made laboratory analyses of 20 sediment cores from the Monterey Bay, California, area.

The results obtained by the use of the viscoelastometer appeared to be of the correct order of magnitude for this type of sediment material; however, no independent determination of the rigidity had been made for comparison and verification. Lasswell (15) determined the real part of the complex rigidity in fine grained surficial marine sediments using an interface wave measurement technique, the interface waves being generated by the detonation of blasting caps at the water-sediment interface in shallow water. Lasswell found that although he did obtain reasonable values of rigidity which could be related to those made with the viscoelastometer, he was not able to control the numerous parameters well enough to obtain a satisfactory validation of the method. Consequently, it was necessary that this validation be attempted in a laboratory where better control of environmental conditions could be achieved.

In the present experiment a small area of ocean bottom was simulated in the laboratory using a tank filled with a kaolinite-water mixture. Surface wave propagation experiments were carried out using an electromechanical vibrator as a source rather than explosives.

The rigidity determinations made using the viscoelastometer may be used to calculate the shear wave speed. Measurements of the phase velocity of the surface wave may also be used to calculate the shear wave speed in the sediment. The calculated shear wave speeds may then be used as a basis for comparison between the two methods, the final objective being the validation of the viscoelastometer method.

II. THEORY

A. RAYLEIGH WAVES

Following the development by Grant and West (8), the equations of motion for an elastic solid separate into two different wave equations which imply the propagation of dilatational or compressional waves and rotational or shear waves. Thus, it becomes convenient to represent the displacement vectors in terms of a dilatational displacement potential, ϕ, and a rotational displacement potential, ψ. For a homogeneous, isotropic material the displacement potentials ϕ and ψ and the displacement component v will satisfy the equations:

$$\frac{\partial^2 \phi}{\partial t^2} = \alpha^2 \nabla^2 \phi \qquad [1]$$

$$\frac{\partial^2 \psi}{\partial t^2} = \beta^2 \nabla^2 \psi \qquad [2]$$

$$\frac{\partial^2 V}{\partial t^2} = \beta^2 \nabla^2 v \qquad [3]$$

where α is the compressional wave speed and β is the shear wave speed.

In this experiment, the main concern is with short pulses which implies that we must find the transient rather than the steady state solution to these equations. Since these are usually difficult to obtain, it is easiest to make a

synthesis of steady state solutions using a Fourier transform such that:

$$\phi(r,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \Phi(r,\omega) e^{-i\omega t} d\omega \qquad [4]$$

where

$$\Phi(r,\omega) = \int_{-\infty}^{\infty} \phi(r,t) e^{i\omega t} dt.$$

Substituting [4] into [1] we obtain:

$$\nabla^2\Phi + k_\alpha{}^2\Phi = 0 \qquad [5]$$

where k_α is the compressional wave number $\frac{\omega}{\alpha}$.

Similarly for ψ and V:

$$\nabla^2\Psi + k_\beta\Psi = 0 \qquad [6]$$

$$\nabla^2 V + k_\beta V = 0 \qquad [7]$$

where k_β is the shear wave number, $\frac{\omega}{\beta}$.

It is possible to write solutions to the equations of motion, [5], [6], and [7] for surface waves whose displacements are largely confined to the neighborhood of the boundary itself. For a plane wave disturbance along an interface between medium 1 and medium 2 containing mixed compressional and vertical shear components travelling with speed c in the x- direction in the x-z plane, it has been shown that the following expressions for ϕ, ψ and V are obtained (8):

$$\Phi_1 = A_1 e^{ik(x+r_1 Z)}$$

$$\Psi_1 = B_1 r^{ik(x+s_1 Z)} \qquad [8]$$

$$V_1 = C_1 e^{ik(x+s_1 Z)}$$

$$\Phi_2 = D_2^{ik(x-r_2 Z)}$$

$$\Psi_2 = F_2 e^{ik(x-s_2 Z)} \qquad [9]$$

$$V_2 = H_2 e^{ik(x-s_2 Z)}$$

where

$$r_n = \left(\frac{c^2}{\alpha_n^2} - 1 \right)^{1/2}, \quad s_n = \left(\frac{c^2}{\beta_n^2} - 1 \right)^{1/2} \text{ and } k = \frac{\omega}{c} .$$

For the particular case of a free boundary (e.g., where medium 1 is a vacuum, in which the components of stress vanish at the surface), it has been shown that the following expression is obtained:

$$\frac{c^6}{\beta^6} - 8 \frac{c^4}{\beta^4} + c^2 \left(\frac{24}{\beta^2} - \frac{16}{\alpha^2} \right) - 16 \left(1 - \frac{\beta^2}{\alpha^2} \right) = 0 \qquad [10]$$

If $c = \beta$, the left-hand side of [10] is equal to 1, while for $c = 0$ it becomes $-16(1 - \beta^2/\alpha^2)$ which is less than 0. This implies that a real root for c exists between $c = 0$ and $c = \beta$. Such a value makes r_2 and s_2 both imaginary; thus, by substitution in equations [8] we can see that the waves are damped exponentially as they enter the medium:

$$\Phi = Ae^{K(ix-rZ)}$$

$$\Psi = Be^{k(ix-sZ)} \qquad [11]$$

$$V = Ce^{k(ix-sZ)}$$

This suggests that a bounded elastic solid permits the propagation of a wave motion along its free surface which attenuates with the depth and travels with a speed less than the shear wave speed of the medium. Such waves are called Rayleigh waves. They are non-dispersive since their speed does not depend upon frequency.

B. THE VISCOELASTOMETER

The viscoelastometer consists of a rod shaped torsional mechanical oscillator which is excited at one of its mechanical resonance modes by a torsional piezoelectric crystal located at its center so that a standing wave is set up along the axis of the system. The torsional motion of the rod surface in contact with another medium generates a shear wave which propagates radially outward from the rod. The radiation of this wave in turn reacts on the rod to change the mechanical damping and mechanical resonance frequency. The loading effects of air are negligible. However, when placed in a more rigid medium such as a soft clay, the loading effects of the medium cause a measurable change in the mechanical damping and in the resonance frequency. These changes are determined by making electrical measurements on the torsional wave transducer.

Following the development by Mason (16), assuming that the wavelength of the shear waves propagating radially outward into the medium in contact with the walls of the rod is very small compared to the radius of curvature of the rod, and that their amplitude is rapidly attenuated, these waves can be treated essentially as plane waves propagating in a fluid having a shear viscosity coefficient, η. Shear waves propagating in the z=direction having amplitude T have the form:

$$T = T_o \exp [(\pi f \rho/\eta)^{1/2} (1+i)z] \qquad [12]$$

where T_o is the initial stress amplitude, f is the frequency and ρ is the fluid density. The simple harmonic time term has been suppressed. The shear viscosity coefficient in a Newtonian fluid is $\eta = T/\dot{S}$, where S is the shear strain and $\dot{S} = \frac{\partial s}{\partial t}$ is the shear "speed." Assuming the medium is visco-elastic, η becomes complex and:

$$\eta_c = \eta_1 - i\eta_2 \qquad [13]$$

where η_1 is the real part and η_2 the imaginary part of the shear viscosity coefficient. In a Newtonian fluid $\eta_2 = 0$, and in a perfectly elastic solid $\eta_1 = 0$. The medium may also be characterized by a complex rigidity modulus:

$$G_c = G_1 + iG_2 \qquad [14]$$

where G_2 is zero in a perfectly elastic solid and G_1 is zero in a Newtonian fluid. Since $\eta_c = T/i\omega S = -iG_c/\omega$ for simple

harmonic motion, where ω is the angular velocity, the following relation may be shown to be true:

$$G_1 = \omega\eta_2 \quad \text{and} \quad G_2 = \omega\eta_1 \ . \qquad [15]$$

The specific radiation impedance (Z) presented to the surface of the rod by the sediment is defined as the ratio of shear stress to particle velocity:

$$Z = (R+ix) = (\pi f\eta\rho)^{1/2}(1+i) \qquad [16]$$

where R is the specific acoustic reactance, X the impedance and ρ the density of the sediment. For the case of a complex viscosity in the equations relating G and η, the real and imaginary parts may be separated to yield

$$\eta_1 = \frac{2RX}{\omega\rho} \qquad \eta_2 = \frac{R^2-X^2}{\omega\rho} \qquad [17]$$

$$G_1 = \frac{R^2-X^2}{\rho} \qquad G_2 = \frac{2RX}{\rho} \qquad [18]$$

This implies that the complex rigidity or viscosity may be determined if the real and imaginary parts of the specific acoustic impedance for plane shear waves is known.

Mason (16) has shown that R and X are related to the change in resonant frequency, Δf, and the change in electrical resistance, ΔR_e, of the transducer driving the system by the equations:

$$\Delta R_e = k_1 R_T \qquad [19]$$

$$\Delta f = k_2 X_T \qquad [20]$$

where $R_t = R/L$ and $X_t = X/L$, and L is the length of the rod in the sediment.

The constants k_1 and k_2 may be evaluated by measuring the resonance frequency and electrical resistance at resonance of the transducer for the rod in air and then measuring these parameters after the rod has been immersed in a Newtonian fluid of known viscosity. Since $\eta_2 = 0$ in Newtonian fluids, $R = X$, and measurement of ΔR_e and Δf permits calculation of R and X. Once k_1 and k_2 are known, R and X in the sediment are determined by measuring ΔR_e and Δf.

III. EQUIPMENT AND PROCEDURE

A. THE SEDIMENT TANK

Saturated kaolinite sediment for the model ocean floor was contained in a 4-ft x 8-ft x 3-ft steel tank (Figure 1). As shown in the cross-sectional diagram, the tank rests on 9 inches of sand and is surrounded to half its height by 1 ft of sand. The sand acts as a damping mechanism for reflections of waves from the walls of the tank and for floor vibrations. Kaolinite clay (hydrated aluminum disilicate) was chosen as the test sediment because its grain diameter is comparable to the clay size particles found in many ocean bottom sediments and it is easily obtained in a fairly pure state.

The bottom of the tank is covered with a layer of ½-inch diameter copper tubing through which steam could be passed for heating the clay. This heating was done soon after mixing the dry clay with water in order to reduce the probabilities of air bubbles existing in the sediment during the course of the experiment. Over a 2-week period the tank was heated to approximately 30°C above room temperature. It was then allowed to cool back down to room temperature before the data were taken. The depth of the sediment was about 22 inches.

B. RAYLEIGH WAVE SPEED MEASUREMENTS

A surface wave is generated in the sediment using a small electrodynamic vibrator which causes vertical oscillations of a 3.3-cm diameter disk in contact with the sediment surface (Figure 2). The electrical drive to the vibrator consists of a gated sine wave, usually four cycles, which is provided by a system consisting of an oscillator, a General Radio tone burst generator and a power amplifier. A block diagram of the apparatus is shown in Figure 3.

The wave motion is sensed using several (usually four) vertically-polarized, velocity-sensitive geophones which are set in contact with the surface at several distances from the source. The electrical signals are amplified in a special four-channel amplifier with variable gain (up to 50 dB) and displayed on a dual-trace cathode ray oscilloscope. The system is triggered by the gate from the tone burst generator. Time delays are determined from a calibrated sweep.

The Rayleigh wave speed is then calculated from the time delays between the various geophones. Six combinations of the four geophones are possible, allowing six calculations of the speed for each array of phones. Observations were made at frequencies from 75 Hz to 300 Hz.

After some experimentation the surface of the sediment was covered with a thin plastic sheet upon which the geophones were placed. The plastic sheet, although having no effect on the surface wave speed, was advantageous for

several reasons. It prevented evaporation from the surface during the course of the experiments, kept the surface from being disturbed due to indentations from the geophones and provided excellent coupling of the geophones to the surface by virtually eliminating any adverse effects caused by frictional drag.

C. THE VISCOELASTOMETER

The viscoelastometer used in this experiment is the same piece of equipment used by Bieda (2) and Lasswell (15). It is a refinement of the original device constructed and evaluated by Cohen (5) and Hutchins (14). Its design reflects the adaptation of a torsional vibrator previously used to measure the shear elastic properties of viscoelastic liquids.

The instrument itself is a 10-1/2 inch long, 1/2 inch diameter cylindrical rod whose torsional oscillation is controlled by a hollow barium titanate transducer mounted in the center of the rod (Figure 6). The transducer is 1-1/2 inches long and 1/2 inch in diameter. It is constructed from an axially-polarized cylinder which was cut into two parts along the longitudinal axis and rejoined after the inversion of one half and the insertion of two electrode grids. The transducer is wrapped in fiberglass thread under tension and covered with an epoxy resin to improve the contact at the joints. The rod is constructed from two sections of a constant modulus alloy, NI-Span-C. These parts were heat treated and are highly polished.

The viscoelastometer is supported by a tubular steel framework which houses the electrical leads to the transducer. The rod is secured to the framework by a clamp at the center of the transducer. In this way the clamp does not interfere with the functioning of the viscoelastometer since the transducer center is a node of torsional motion for all the resonant modes. The electrical connections are kept watertight by the application of a silicone rubber coating.

As mentioned previously the rod was first calibrated in Newtonian fluids of known viscosity to obtain the constants k_1 and k_2. The resonant frequency and electrical resistance were then measured in air and in the artificial sediment in order to obtain Δf and ΔRe needed to calculate the rigidity as explained in Section II-B. Two glass tubes sealed at the bottom had been inserted in the sediment, one filled with a Newtonian fluid and the other empty. The measurements for the Newtonian fluid and the air were made in these to insure that the measurements in these media were made at the same temperature as those made in the kaolinite.

A General Radio oscillator capable of fine adjustments in frequency was used to excite the torsional oscillation in the viscoelastometer. The electrical measurements were carried out using a Dranetz complex impedance-admittance meter and a Hewlett-Packard electronic frequency counter.

D. COMPRESSIONAL WAVE VELOCIMETER

The compressional wave speed is determined by measuring the time of travel for a 2-MHz pulse through a known length of the kaolinite-water mixture.

The compressional wave velocimeter consists of two barium titanate disk transducers mounted one above the other. The upper transducer is pulsed at approximately 2 MHz in order that it may operate in a resonant mode to obtain maximum efficiency (Figure 7). A dual-beam oscilloscope, a wide-band amplifier, a pulsed oscillator, a time mark generator and a dial indicator good to 0.003 cm were also used in this portion of the experiment.

The calibration of the velocimeter was performed in a mixture of 22 parts ethanol and 100 parts distilled water. This particular mixture was chosen in order to minimize the dependence of the sound velocity on temperature (20). The sound speed was determined from a series of measurements in the mixture over distance measured on the dial indicator using the time mark generator as a time base with which to measure the time delay between the transmitted pulse and the received pulse. It was then possible to extrapolate these points to a zero time delay which gave a measure of the actual transducer spacing.

The compressional wave speed in the sediment was measured in samples contained in 2-1/2 inch diameter plastic coring tubes, 2 to 2-1/2 inches in length. The bottom of each recovered core tube was covered with a thin layer of

plastic and then inserted between the receiving and transmitting transducers. Tests were made for three to four depths of penetration of the transmitting transducer in each sample. In order to obtain some indication of the degree of homogeneity of the clay in the tank, samples were collected at the surface at several positions and at several depths.

E. WET DENSITY AND POROSITY

The wet density is the weight per unit volume of the water-saturated sample. This was determined by placing the water-saturated kaolinite in a small metal cylinder of known volume. The weight of the cylinder was measured before and after filling in order to determine the sample weight.

The porosity (P) of a material is the fraction of voids present in a given volume of the material. This was determined by heating the known volume of water-saturated kaolinite sediment for 24 hours at 105°C. The cylinder and sample were then weighed again, and assuming that the total weight loss is due to the evaporation of water (1 ml = 1 g = 1 cc), the porosity is then equal to the ratio of the volume lost due to heating to the original volume:

$$P = \text{Volume of voids/Total volume.}$$

IV. RESULTS AND DISCUSSION

Table I shows the results for the surface wave speed measurements in the tank. It is believed that the disturbance observed was a Rayleigh wave since our boundary conditions are essentially the same as those necessary for a Rayleigh wave (i.e., zero stress at the surface).

Extensive attempts were made to determine the detailed character of the surface wave by means of attenuation measurements. Shear waves diverging in three dimensions should be attenuated with respect to the reciprocal of the distance from the source while Rayleigh waves, diverging in two dimensions, should attenuate with the reciprocal of the square root of the distance from the source. However, numerous log-log plots of observed wave amplitudes vs. distance from the source gave inconclusive results. Although the signals received were very clear, the attenuation seemed to be extremely variable, especially at distances beyond 30 to 40 cm from the source. This variability may have been caused by absorption in the sediment or by differences in response or coupling among the geophones.

There are also indications that these amplitude variations at larger ranges may have been caused by interference effects between direct and wall-reflected waves. These effects had also been observed during attempts to measure the wave length and frequency of a continuous wave generated

by the source. Observations to determine wave speed for continuous waves were made by phase matching using Lissajous figures on the oscilloscope. Consistent values could not be obtained due to interference effects.

Coupling between the geophones and the sediment surface proved to be very important in the Rayleigh wave amplitude measurement, possibly related to some of the microstructure of the sediment. Nevertheless, it was determined that although the response from the geophones was occasionally poor upon initial placement on the surface, an extremely good response was observed after approximately 1/2 hour to 1 hour of "coupling time." These difficulties had little effect on the wave speed measurements using the gated sine wave method.

Table II shows the results of the tests on compressional wave speed, porosity and wet density. The values obtained show an acceptable degree of homogeneity for the experiment especially at the surface layer. Some variability is evidenced with depth as would be expected.

Unfortunately, due to a sequence of events described below, no correlatable data were obtained from measurements made with the viscoelatometer. When the measurements were first attempted in the sediment with the device used by Lasswell and Bieda, water leaked into the transducer due to a breakdown in the sealing. During correction of this leakage the transducer was mechanically damaged. Another transducer was then constructed for the device. Subsequent

measurements showed an increased sensitivity and apparent stability in air for the first three modes over a 24-hour period. The new viscoelastometer was then placed in mud. Unexpectedly, the data taken showed a 25 to 30 Hz increase in resonant frequency under loading. The device was then checked in Newtonian calibration fluids where it displayed the expected decrease in resonant frequency and yielded consistent readings over a 24-hour period; however, upon removal from the Newtonian fluid, the rod failed to stabilize at its former resonant frequency in air.

These anomalous results are believed to be related to some defect of unknown origin in the construction of the present transducer. The viscoelastometer, when used by Lasswell and Bieda, had functioned very well in sediments of like density, porosity and compressional wave speed.

V. ESTIMATE OF ERROR

The shear wave speed was calculated from the Rayleigh wave speed using equation [10] where it has been assumed that the compressional wave speed, α, is very much greater than the shear wave speed, β. Equation [10] then reduces to

$$\frac{c^6}{\beta^6} - 8\,\frac{c^4}{\beta^4} + 24\,\frac{c^2}{\beta^2} - 16 = 0 \qquad [21]$$

which has the solution in c, $c = .95\beta$ (7). This assumption could affect the accuracy of the shear wave speed by no more than 1%.

The wave forms observed on the oscilloscope were well-defined and easily traced from one geophone to the next as shown in Figure 5. The time delay was measured between the first minimum points on the wave forms being considered. A maximum error of 1% may have been introduced at this point.

Some error may have been introduced in the measurement of the separation distance between geophones which was only accurate to within 0.5 cm. This could result in a maximum error of about 5%.

As a result the total possible error is estimated at 7%. A typical standard deviation of the observed Rayleigh wave speeds was about 4% for all frequencies. The standard deviation of these averages from the average value over the frequency range of 75 Hz to 300 Hz was 2% (Table I).

VI. CONCLUSIONS AND RECOMMENDATIONS

An experimental method has been used to determine the speed of propagation of simple harmonic surface waves, believed to be Rayleigh waves, in a kaolinite-water mixture. Measurements over the range of frequencies between 75 Hz and 300 Hz have shown no evidence of dispersion. The limit of precision is of the order of 5%. The value of the calculated shear wave speed, about 23 m/sec, compares in order of magnitude with values reported by others (1, 12, 15) in somewhat similar sediments. No data were obtained using the viscoelastometer in the kaolinite-water mixture used for the surface wave experiments due to experimental problems. However, viscoelastometer data were obtained by Bieda (2) and Lasswell (15) in sediments of similar porosity, density and compressional wave speed. Their results, expressed in terms of shear wave speed, fall in the 20 m/sec to 30 m/sec range. Therefore, the results obtained in the surface wave experiments here tend to confirm the validity of the previously reported results for the viscoelastometer. Further efforts are needed to solve the current problems with the viscoelastometer in order to get a more quantitative estimate of its validity. The tank has proven to be an effective three-dimensional model for Rayleigh wave propagation. It is believed that a good quantitative estimate of

validity could be made once the proper functioning of the viscoelastometer is insured.

A number of recommendations may be made. Results by Hamilton, et al. (12) from in situ measurements of the Stoneley wave speed in Southern California continental margin sediments not vastly different from the kaolinite clay used here give values of the order of 100 m/sec. It would be interesting to determine the cause of the rather large differences from the values obtained in this experiment. The most obvious effects which should be considered are those of temperature and hydrostatic pressure. The correlation with other mechanical properties should be examined as well.

Further investigation is also necessary to determine the detailed character of the waves generated in the tank. This could be done using attenuation measurements or possibly by using a sensor capable of determining the initial motion of surface particles affected by the wave propagation. If this motion has a horizontal component and is retrograde, the assumption that these are free Rayleigh waves will be confirmed. Investigation into attenuation measurements, once the detailed nature of the disturbance has been determined, might also be valuable as a means of determining the absorption characteristics for shear wave propagation in such a medium. Before measurements of this type could be made it would be essential to have geophones of equal or calibrated response and equally well "coupled" to the sediment surface.

The problem of coupling might also be investigated. Serious studies along these lines would probably involve a thorough investigation of the details of interaction at the surface between the soft mud and the detecting instrument.

TABLE I

SHEAR WAVE SPEED AT VARIOUS FREQUENCIES

Freq (Hz)	$C_{Rayleigh}$ (m/sec)	β (m/sec)	Stand.Dev. (m/sec)
75	20.8	21.9	.9
100	22.1	23.2	.9
150	22.3	23.4	.9
200	21.7	22.6	.8
250	22.0	23.1	.9
300	22.4	23.6	.6

TABLE II

HORIZONTAL AND VERTICAL VARIATIONS IN PROPERTIES OF SEDIMENT SAMPLES FROM VARIOUS POSITIONS IN THE TANK

Surface Samples

Sample #	Temperature (°C)	Wet Density (gm/cm^3)	Porosity (%)	α (m/sec)	$\alpha_{sed}/\alpha_{water}$	Poisson's Ratio
1	20.2	1.45	66.9	--	--	--
2	22.0	1.47	65.6	1464	.987	.499
3	21.8	1.46	65.7	1466	.993	.499
4	21.0	1.45	66.8	1470	.995	.499
5	21.2	1.48	65.0	1470	.994	.499

Vertical Cross-section

Sample #	Temperature (°C)	Depth (cm)	Wet Density (gm/cm^3)	Porosity (%)	α (m/sec)	$\alpha_{sed}/\alpha_{water}$	Poisson's Ratio
6	21.8	0	1.46	65.7	1466	.993	.499
7	20.4	20	--	--	--	--	--
8	21.0	33	1.47	64.9	1458	.987	.499
9	21.3	43	1.50	64.2	1464	.990	.499
10	21.4	53	1.52	53.4	1479	.999	.499

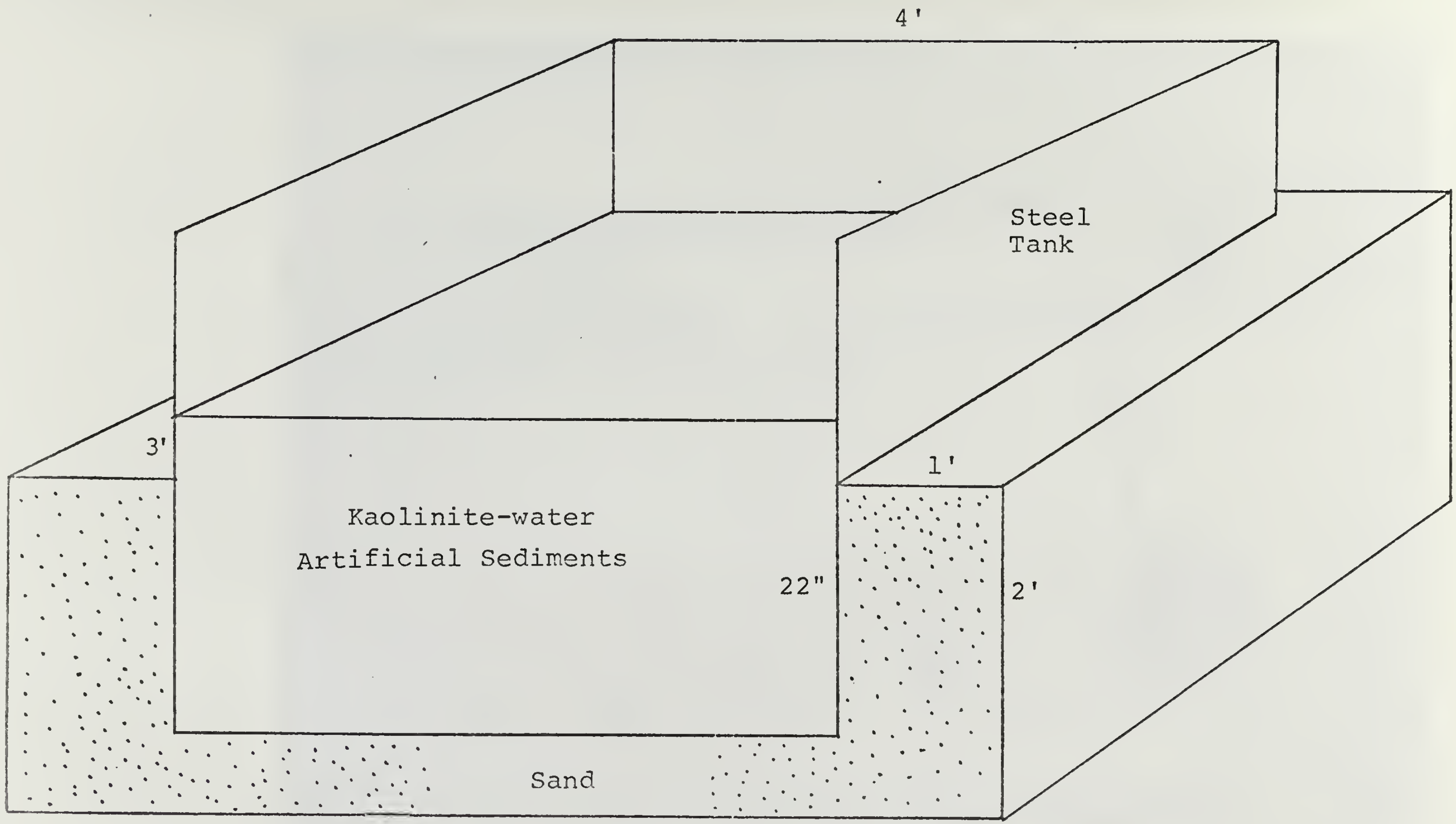

Figure 1. Cross-sectional view of the tank.

Figure 2. Source and geophones.

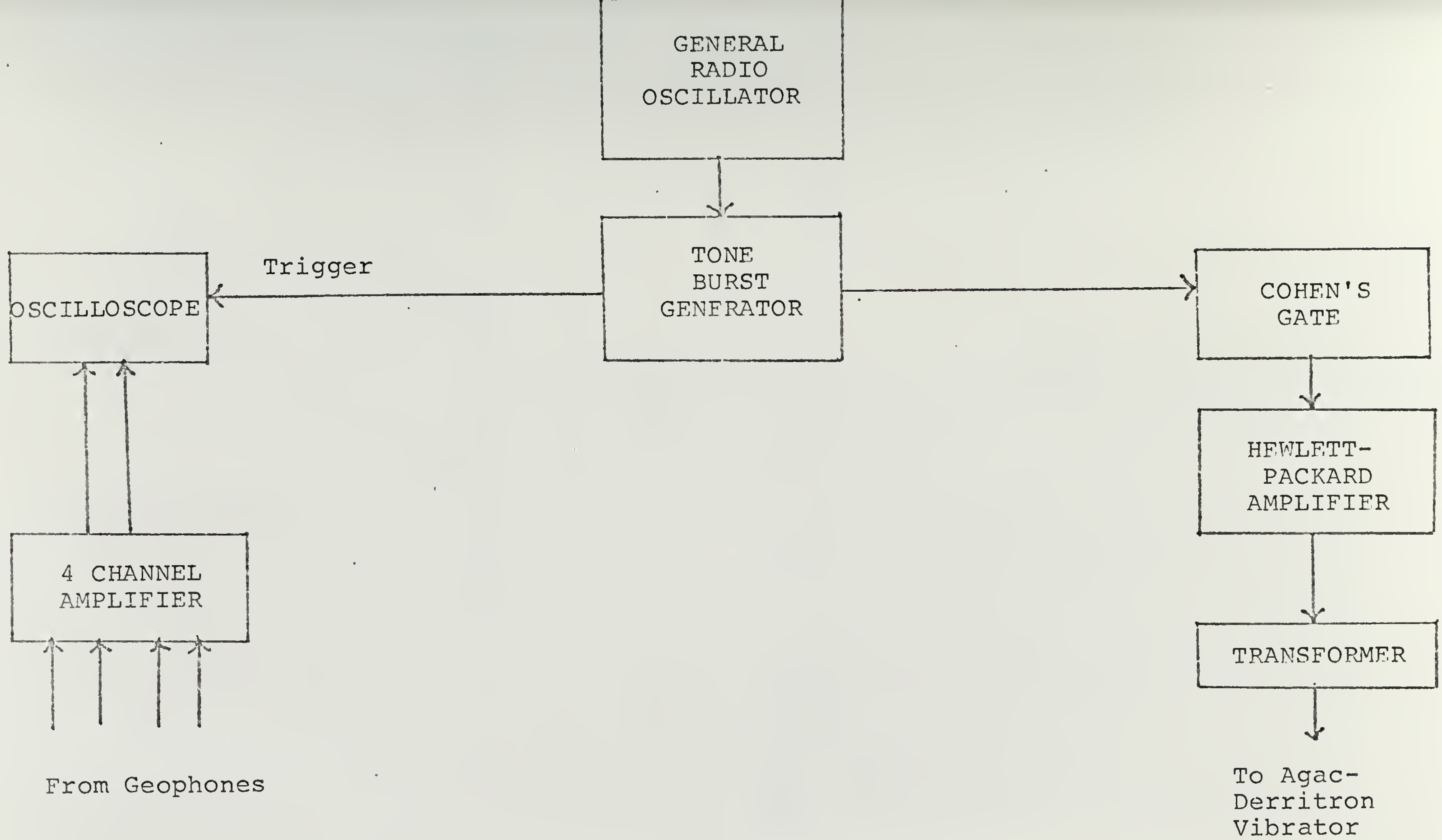

Figure 3. Block Diagram for Operation of Source and Geophones.

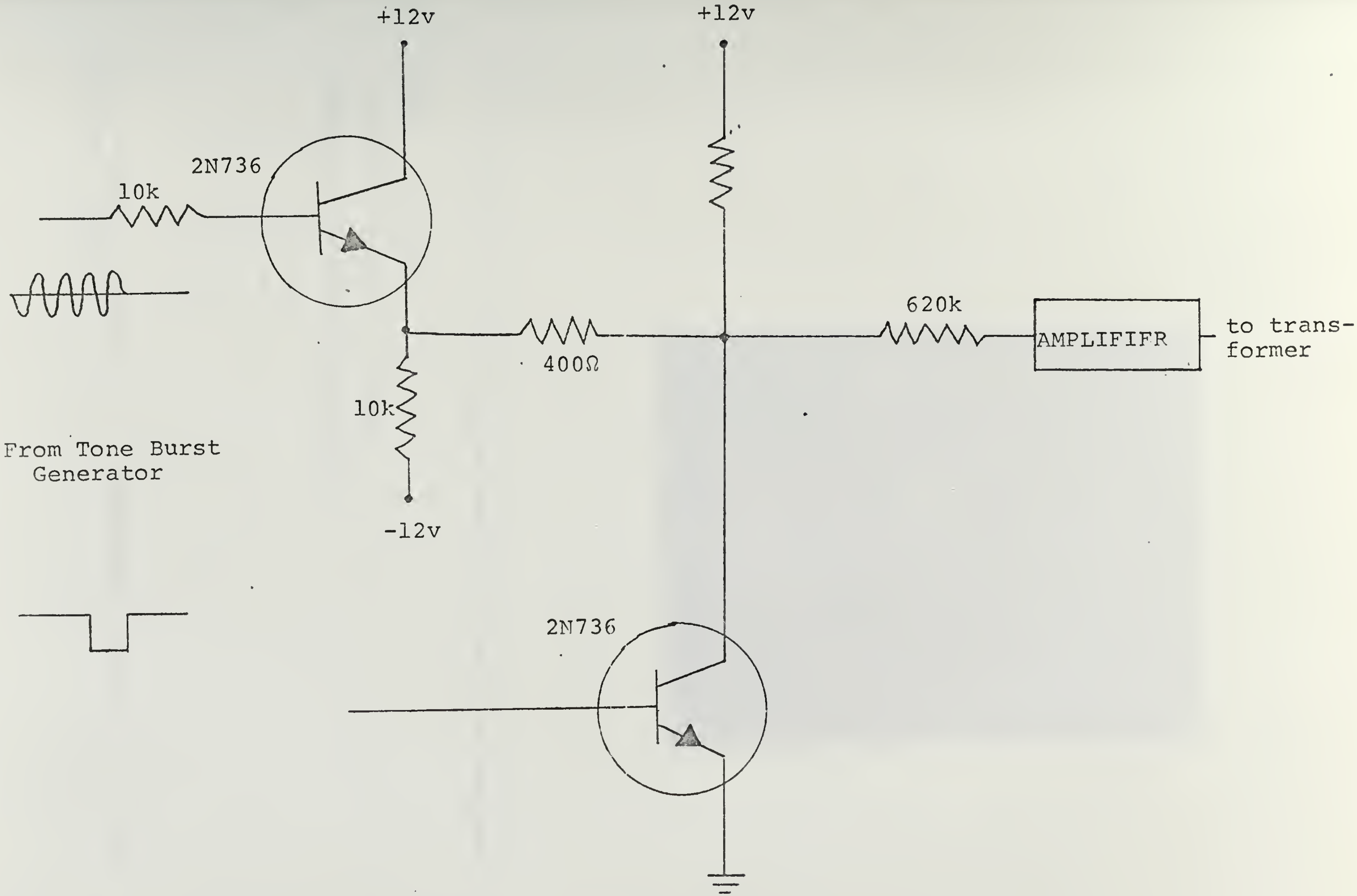

Figure 4. Cohen's Input Gate.

a.

b.

c.

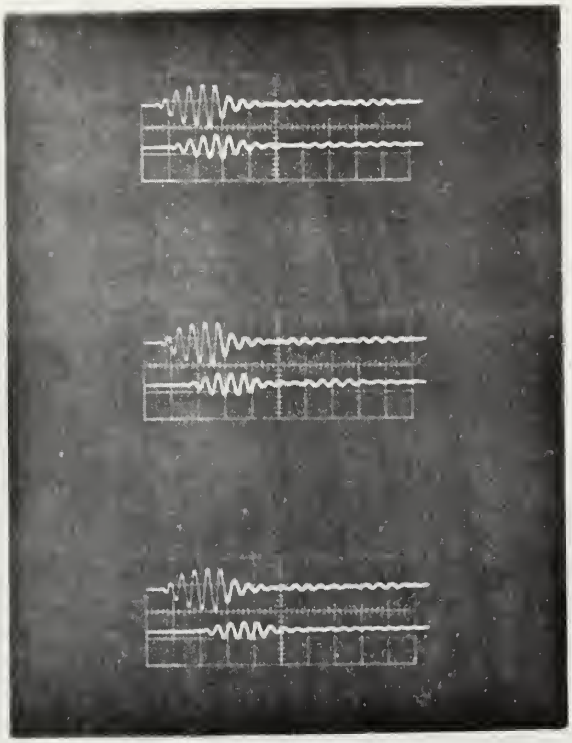

Figure 5. Oscilloscope Record of Geophone Response.

Freq. - 200 Hz

1 Scale Division - 10 μsec.

Geophone Distance from Source:

#1. 10.7 cm

#2. 21.8 cm

#3. 31.2 cm

#4. 42.1 cm.

a. Geophones 1 and 2; b. Geophones 1 and 3; c. Geophones 1 and 4.

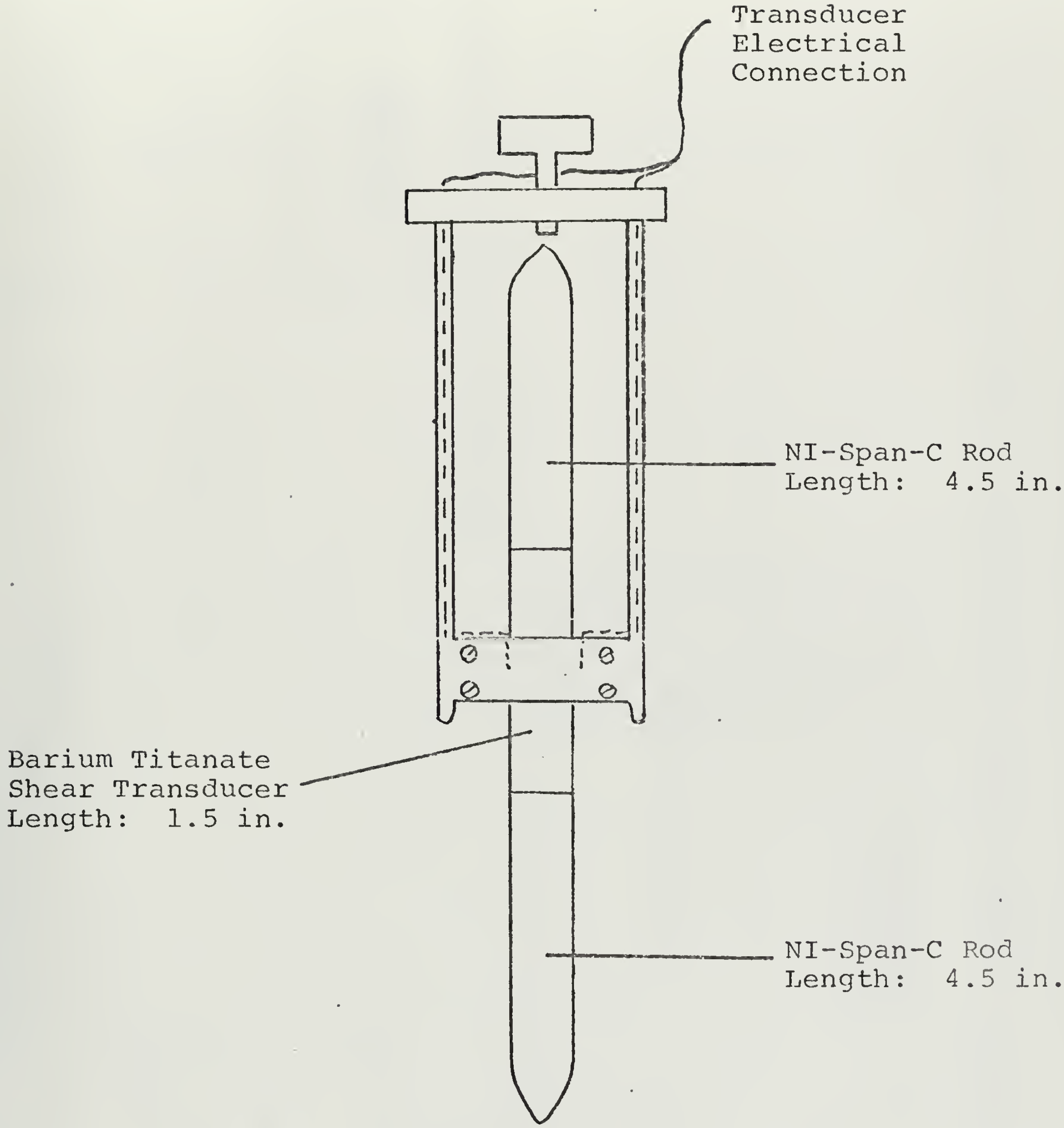

Figure 6. The Viscoelastometer.

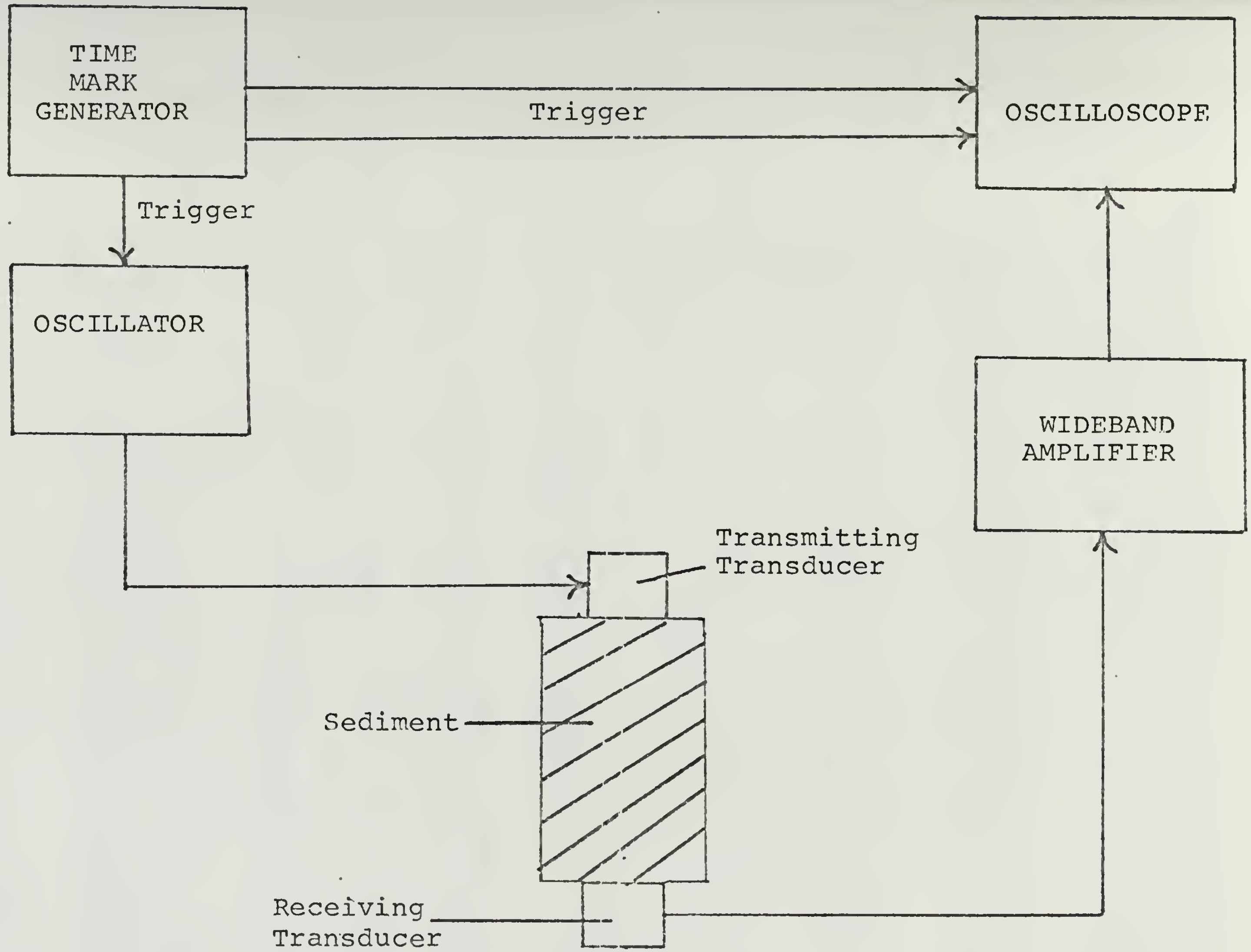

Figure 7. Block Diagram for Operation of Sound Velocimeter.

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13. ABSTRACT

A three-dimensional model for the study of surface wave speed measurements in simulated ocean bottom sediments has been constructed using a high-porosity kaolinite-water mixture in a rectangular tank in the laboratory. The propagation of surface waves, assumed to be Rayleigh waves, was studied over the 75 Hz to 300 Hz frequency range using a gated sine wave source and several geophone receivers. Shear wave speeds in the sediment are determined to be 23 m/sec. These measurements are qualitatively compared with measurements made by previous investigators in similar sediments using a torsionally oscillating rod viscoelastometer whose resonant characteristics are sensitive to loading by the sediment in which it is imbedded. Good correlation of results is found with the shear wave speeds calculated from the viscoelastometer data which are in the range of 20 to 30 m/sec.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
RAYLEIGH WAVE						
VISCOELASTIC						
SHEAR WAVE SPEED						

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